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# Spatio-temporal hydro-climate variability in Finland

A master's thesis submitted for inspection for the degree of Master of Science in Technology.

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**Abstract of master's thesis**

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**Abstract** The climate in Finland is changing – temperature and precipitation are increasing, resulting in varying runoff patterns. These hydro-climatic trends have been well studied previously, but the changes in variability are less known, despite their importance for understanding climate change. This research aims to assess spatio-temporal changes in variability of temperature, precipitation and runoff for the years 1962-2014 at sub-basin scale in Finland. Temporal changes in variability were analyzed by constructing moving window median absolute deviation (MAD) time series at both annual and seasonal scales. Areas with similar patterns of variability were then identified using principal component analysis (PCA) and agglomerative hierarchical clustering. Direction and statistical significance of changes in MAD were studied using a test for a monotonic trend in variances. Distinct areas with similar patterns of statistically significant change in variability were found. With regard to temperature, this study found decreases in annual and winter variability in most parts of Finland, as well as summer variability in northern Finland. In terms of precipitation, decreases were identified for annual variability in the south of Finland, for spring variability in the central part of the study area and for autumn variability in southeastern Finland, as well as increases for autumn variability in northern Finland. For runoff, variability increased in winter in most parts of the study area and in summer in the central part of the study area, as well as decreased in spring in southern Finland. Comparison with previous studies illustrates how trends in mean climate and its variability do not necessarily match; both aspects need investigation. Findings of this study provide new information on hydro-climatic variability in Finland and improve the possibility to adapt and predict the changes in hydro-climatic conditions, including intensity and frequency of weather extremes.

**Keywords** Finland, climate change, climate variability, hydro-climate, temperature, precipitation, runoff

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**Tiivistelmä** Suomen ilmasto muuttuu – lämpötila ja sadanta kasvavat, ja valunnan määrässä sekä ajoituksessa tapahtuu muutoksia. Ilmaston ja hydrologisen kierron keskimääräisten olosuhteiden muutoksia on tutkittu laajasti aikaisemmin, mutta vähemmälle huomiolle ovat jääneet lyhyen aikavälin muutokset, kuten vuosien ja vuodenaikojen välinen vaihtelu sekä näiden muutokset. Lyhyen aikavälin vaihtelun tutkiminen on tärkeä osa ilmastonmuutoksen ymmärtämistä ja siihen sopeutumista. Tämän tutkimuksen tarkoitus oli määrittää lämpötilan, sadannan sekä valunnan vuosien ja vuodenaikojen välisen vaihtelun muutoksia Suomessa osavaluma-aluetasolla vuosina 1962–2014. Vaihtelun muutoksia ajan suhteen analysoitiin muodostamalla hajonta-aikasarjoja käyttäen liukuvia MAD-analyysi-ikkunoita (median absolute deviation). Alueet, joiden sisällä vaihtelun muutos on ollut samankaltaista, tunnistettiin hajonta-aikasarjoista pääkomponentti- ja klusterianalyysien avulla, minkä jälkeen muutosten suuntaa ja tilastollista merkittävyyttä arvioitiin testillä, joka tunnistaa monotonisia trendejä variansseissa. Tutkimuksessa löytyi selkeitä alueita, joilla vaihtelun muutos on ollut samankaltaista ja tilastollisesti merkittävää. Lämpötilan vaihtelu vuosien sekä talvien välillä on vähentynyt lähes koko Suomen alueella, ja kesien välillä Pohjois-Suomessa. Sadannan vaihtelun vähentymistä vuosien välillä havaittiin Etelä-Suomessa, keväiden välillä tutkimusalueen keskiosissa ja syksyjen välillä Kaakkois-Suomessa. Vaihtelu kasvoi syksyjen välillä Pohjois-Suomessa. Valuntaa tarkasteltaessa vaihtelun kasvua havaittiin lähes koko tutkimusalueella talvien välillä sekä tutkimusalueen keskiosissa kesien välillä. Etelä-Suomessa havaittiin vaihtelun vähentymistä keväiden välillä. Tulosten vertaaminen aikaisempiin tutkimuksiin osoitti, että muutokset ilmaston ja hydrologisen kierron keskimääräisissä olosuhteissa eivät välttämättä tarkoita samansuuntaisia muutoksia lyhyen aikavälin vaihteluissa – molemmat tekijät vaativat tutkimusta. Tämän tutkimuksen tulokset antavat uutta tietoa Suomen ilmaston ja hydrologisen kierron vaihtelusta sekä parantavat mahdollisuutta ennustaa sen muutoksia ja sopeutua muun muassa äärisääilmiöiden voimakkuuden ja esiintymistiheyden muuttumiseen.

**Avainsanat** Suomi, ilmastonmuutos, ilmaston vaihtelu, hydrologia, lämpötila, sadanta, valunta

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# Table of contents

Abstract of master's thesis
Diplomityön tiivistelmä
Acknowledgements
Table of contents
1 Introduction ... 6
2 Data and methodology ... 9
2.1 Data ... 9
2.2 Detecting hydro-climatic trends ... 10
2.3 Quantifying hydro-climatic variability ... 10
2.4 Identifying areas with similar hydro-climatic variability ... 11
2.5 Detecting direction and statistical significance of changes in hydro-climatic variability ... 12
3 Results ... 13
3.1 Hydro-climatic trends in study area scale ... 13
3.2 Temporal changes in hydro-climatic variability in study area scale ... 14
3.3 Spatial patterns in changing variability and statistical significance of changes ... 15
4 Discussion ... 22
4.1 Comparison to previous studies ... 22
4.2 Limitations of the present study ... 23
4.3 Future research directions ... 23
5 Conclusions ... 25
References ... 26

# 1 Introduction

Climate change and global warming are unequivocal. According to the Intergovernmental Panel on Climate Change (IPCC), global average temperature has increased 0.85 (0.65 to 1.06) °C during the period 1880 to 2012 (IPCC, 2015) and during the second half of the period, temperature have increased even more rapidly. Warming is greater at higher northern latitudes, where the study area of this paper is located. Global warming is highly linked to components of the hydrological cycle, e.g. precipitation patterns (amount, frequency and intensity). Warming temperatures as well as changing precipitation causes shifts in runoff regime, and changes in hydro-climate have been projected to continue in future (IPCC, 2015).

Climate change usually refers to changes in climate over time, caused by natural fluctuations or anthropogenic forces, i.e. human activities (IPCC, 2015). In other words, climate change is a significant change in the average weather conditions for a region over a longer period of time. Measures such as mean state, natural variability and extreme events can be included when climate is studied. The focus of the present study is on climate-induced changes in hydro-climatic variability, rather than trends in hydro-climatic mean conditions. Climate variability refers to variations around the mean state of the climate or other climate statistics, i.e. standard deviations or the occurrence of extremes, on different temporal and spatial scales (IPCC, 2015). Variability in hydro-climate can be caused by natural internal processes of the climate system (internal variability) or from variations in natural or anthropogenic external forces (external variability).

The understanding of hydro-climatic variability is important, including for Finland, specific area of interest in this study. Changes in hydro-climatic variability have impacts on the intensity and frequency of extreme events, for which society and nature can be particularly vulnerable (Thornton *et al.*, 2014). For example, an increase in hydro-climatic variability implies an increase in extremes relative to mean hydro-climate. Different sectors of society and nature are affected differently by possible changes in hydro-climatic variability, both positively and negatively. Some examples of these affected sectors are agriculture and livestock, and consequently also economy and food production; forestry, which is economically important for Finland; natural ecosystems can experience changes; as well as tourism industry and water sector e.g. water availability, water supply and hydropower (Maracchi *et al.*, 2005; Marttila *et al.*, 2005; Saarinen and Tervo, 2006; Lehtonen and Kujala, 2007; Kellomäki *et al.*, 2008; Tervo, 2008; Peltonen-Sainio *et al.*, 2009).

Some previous studies at regional and global scale focus on climate variability and related aspects, with relevance to Finland. Fischer & Schär (2009) projects weak changes in variability of summer temperature in northern Europe and several studies (Räisänen, 2002; Giorgi *et al.*, 2004a, 2004b; Schär *et al.*, 2004; Giorgi and Bi, 2005) project changing trends in winter and summer variability of temperature as well as precipitation in global and continental scale in Europe. There are also several studies focusing on aspects related to climate variability, for example temperature and/or precipitation extremes in global scale (Tebaldi *et al.*, 2006), in Nordic countries (Tuomenvirta *et al.*, 1998, 2000) and in Europe (Frei *et al.*, 2006); droughts and floods in Nordic countries (Hisdal *et al.*, 2006; Veijalainen *et al.*, 2010; Wilson *et al.*, 2010); role of teleconnections, for example North Atlantic Oscillation (Marshall *et al.*, 2001; Wanner *et al.*, 2001; Hurrell *et al.*, 2003; Uvo, 2003; Grossmann and Klotzbach, 2009; Hurrell and Deser, 2010); as well as millennial-scale climate change and variation in Northern Hemisphere and Europe (Crowley, 2000; Delworth and Mann, 2000; Luterbacher *et al.*, 2004; Moberg *et al.*, 2005).

In this study, the study area includes the whole of Finland, and transboundary watersheds in Norway, Sweden and Russia. Finland is located on at high-latitudes in Northern Europe, on the edge of the Eurasian continent. Geographical position is the main factor influencing climate within Finland. Latitudinal gradient (55-70 °N), the Atlantic Ocean, the combined continental landmass of Eurasia, the Scandinavian Mountain range and the Baltic Sea, all have their own impacts on climate in Finland (Käyhkö, 2004). The climate in Finland is described to be intermediate with characteristics of a maritime (Atlantic Ocean) and a continental (Eurasia) climate.

There are notable differences in hydro-climatic conditions between the seasons. For example, during the winter, the temperature is considerably lower than during the summer, and precipitation falls in form of snow stored in the snowpack, while during the summer, precipitation falls in liquid form with a higher evaporation rate. Snow accumulation and melting are important parts of hydro-climate in Finland and at high latitudes in Northern Hemisphere (Kuusisto, 1984; Irannezhad *et al.*, 2015, 2016). Amount, timing and duration of snowpack have a significant role in storing water during winter and melting at spring, causing peak river discharge. Furthermore, snow conditions in Finland and high-latitudes are projected to change due to climate change (Barnett *et al.*, 2005; Adam *et al.*, 2009). Warming temperature causes less precipitation falling as snow during winter as well as snow melt occurring earlier in spring.

Recent studies show statistically significant increasing trends for country scale averaged temperature (Irannezhad *et al.*, 2014a; Mikkonen *et al.*, 2015) and precipitation (Irannezhad *et al.*, 2014b) in Finland. Mean annual temperature in Finland has increased by 0.4 ± 0.2 °C per decade during the period 1961-2011 (Irannezhad *et al.*, 2014a). Other studies also show increasing trends in annual mean temperature: 0.14 °C per decade during the period 1847-2013 (Mikkonen *et al.*, 2015) and 0.7 °C during 1901-2000 (Jylhä *et al.*, 2004). The warming trend after the 1960s has become steeper, between 0.2 and 0.4 °C per decade (Irannezhad *et al.*, 2014a; Mikkonen *et al.*, 2015). At a seasonal scale, statistically significant increasing trends in mean temperature for spring have been found, 0.4 ± 0.2 °C per decade in 1961-2011 (Irannezhad *et al.*, 2014a) and 1.4 °C per 100 years in 1901-2000 (Jylhä *et al.*, 2004). Furthermore, both Irannezhad et al. (2014a) and Jylhä et al. (2004) found a statistically significant increasing trend in mean temperature for summer (0.3 ± 0.2 °C per decade and 0.7 °C per 100 years).

In terms of precipitation, a study by Irannezhad et al. (2014b) shows that annual mean precipitation in Finland has increased significantly by 0.92 ± 0.50 mm per year during the period 1911-2011. Moreover, significant increases in mean precipitation were found for winter (0.46 ± 0.19 mm per year) and summer (0.32 ± 0.29 mm per year). In contrast, Jylhä et al. (2004) did not found any statistically significant trends in precipitation, over the period 1901-2000, and neither did Tuomenvirta & Heino (1996), over the period 1910-1995.

Trends in runoff are less studied in Finland, but changes in discharge have been studied to some extent and these tend to be quite similar. Previous studies have found increasing trends in annual discharge for most of the area of Finland. A study by Hyvärinen (2003) presents an average increase of 0.5 mm per year, and in southwestern parts up to 1 mm per year during the 20th century. A study about the Nordic countries by Wilson et al. (2010) has found increasing trends in western parts of Finland during the periods of 1941-2005 and 1961-2000. Clear increasing trends have also been found for winter discharge in many regions (Hyvärinen, 2003; Korhonen, 2007; Korhonen and Kuusisto, 2010; Wilson *et al.*, 2010).

Given that trends in hydro-climatic conditions in Finland are well studied, this study focuses on the past changes in hydro-climatic variability. Only a few findings in larger scale studies (Räisänen, 2002; Giorgi and Bi, 2005) have been identified that are relevant for Finland. Giorgi & Bi (2005) projects winter variability of temperature as well as precipitation in northern Europe to decrease, and summer variability to increase on average across an ensemble of general circulation models during the 21st century. Change of standard deviation for winter temperature is projected to be -2.88 °C per decade, and for summer, +1.79 °C per decade. In case of precipitation, change in coefficient of variation for winter is -0.08 % per decade, and for summer, +3.00 % per decade. These projected trends in variability are, however, uncertain, with notable differences between circulation models. Inter-model standard deviation of temperature variability for winter is 3.29 °C per decade and for summer 3.74 °C per decade. For precipitation variability, inter-model standard deviation for winter is 2.75 % per decade and for summer 4.35 % per decade. These results are in line with findings of Räisänen (2002). Both studies were carried out at continental scale (lower resolution) and with future projections. Taking into account that there are notable differences in regional climate conditions, and that these studies do not provide adequate observational evidence of changes, there is a need for a consistent, higher resolution historical analysis of these trends in hydro-climatic variability within Finland, amongst other regions.

The aim of this study is to assess the past spatial and temporal changes in inter-annual hydro-climatic variability in Finland, in terms of both annual average and seasonal patterns. Spatial and temporal changes in variability of temperature, precipitation and runoff were analyzed using a sub-basin scale dataset over the years of 1962-2014. Runoff was selected rather than discharge as it focusses on local sub-catchment processes, excluding inflows, and therefore emphasizes local spatial variation rather than spatial correlations. These hydro-climatic time series were studied using statistical analyses, moving window median absolute deviation to quantifying hydro-climatic variability; principal component analysis and agglomerative hierarchical clustering to discover areas with similar hydro-climatic variability (Mimmack *et al.*, 2001); as well as a test for monotonic trends in variances (Noguchi and Gel, 2010) to identify the directions of changes and whether changes in hydro-climatic variability are statistically significant.

# 2 Data and methodology

Analyses in the present study used annual and monthly sub-basin scale data of mean temperature, precipitation sum and runoff sum for the period of 1962-2014, provided by the Finnish Environmental Institute (SYKE). The areal temperature, precipitation and runoff data were calculated and simulated by Watershed simulation and forecasting system (WSFS) of SYKE based on observed daily temperatures and precipitations.

To begin with, time series for the whole study area were analyzed, namely averaged annual and seasonal mean temperature, precipitation sum and runoff sum. Mann-Kendall trend test was used to detect climate change trends. This was carried out to understand and show the context of changes in hydro-climatic variability with climate change in Finland.

Temporal changes in hydro-climatic variability were then studied by constructing moving window median absolute deviation (MAD) time series of mean temperature, precipitation sum and runoff sum. These were calculated both for the whole study area and for each sub-basin separately. Spatial patterns in changing hydro-climatic variability were studied using principal component analysis and agglomerative hierarchical clustering of the sub-basin MAD time series. By doing so, areas with similar changes in temporal hydro-climatic variability were identified and grouped together. Finally, areas with statistically significant changes in variability and direction of trend were determined using the test for a monotonic trend variances. More detailed description on the data and each analysis follows below.

## *2.1 Data*

The source data used in the present study consisted of annual and monthly values of mean temperature precipitation sum and runoff sum for 6172 sub-basins in Finland including transboundary watersheds in Norway, Sweden and Russia (Finland's Environmental Administration, 2015). The data covered the time period from January 1962 to December 2014. The sub-basin-scale areal temperature and precipitation data were calculated using temperature and precipitation observations from Finnish Meteorological Institute from respectively approximately 190 and 250 observation stations in 2010, though the number varied in time (Veijalainen, 2012). In addition to that, observations for transboundary watersheds from 11 temperature and 16 precipitation observation stations were provided by Norwegian Meteorological Institute, Swedish Meteorological & Hydrological Institute and Hydrometeorological Center of Russia.

To obtain a stable precipitation observation network during the whole time period, missing observation values were calculated from the three closest observation stations, taking into account elevation and aerodynamic corrections (Taskinen and Söderholm, 2016). The method was not used for the temperature data because the temperature observation network was considered to be dense enough to cover the spatial variation for the whole time period.

The sub-basin scale areal meteorological values were then calculated from three closest observation stations by inverse distance weighting, taking into account elevation differences. The sub-basin scale temperature and precipitation data were then used as an input in the HBV-type conceptual hydrological model WSFS, to calculate the runoff data (Vehviläinen *et al.*, 2005; Veijalainen, 2012; Olsson *et al.*, 2015). The study area size is 390,000 km2 in total and the sizes of sub-basins varied mostly between 1 to 6197 km2, with a median of 42 km2. The WSFS has been calibrated with observations of discharges, water levels and snow water equivalents over the period of 1981-2013. For more detailed description of the source data, see Vehviläinen et al. (2005) and Veijalainen (2012).

Seasonal values were calculated from this source data. Seasons were formed by three-month periods: winter (December, January and February); spring (March, April and May); summer (June, July and August) and autumn (September, October and November). The data used in present study thus contained time series of annual and seasonal sub-basin scale mean temperature, precipitation sum and runoff sum for the time period from January 1962 to December 2014.

## 2.2 Detecting hydro-climatic trends

The Mann-Kendall trend test (Mann, 1945; Kendall, 1975) was used to detect possible trends at study area scale for annual and seasonal mean temperature, precipitation sum and runoff sum time series. Mann-Kendall trend test is a nonparametric test, which has been commonly used to detect monotonic trends in climate and hydrological datasets. The test detects if a trend exists in the time series, whether the trend is positive or negative and whether this trend is statistically significant. A bootstrap version (Santander Meteorology Group, 2012) of the Mann-Kendall trend test was used to take into account the possible autocorrelation of the data. A 95% significance level was used for detecting trends.

## 2.3 Quantifying hydro-climatic variability

MAD was used to examine the variability of hydro-climatic variables, i.e. how hydro-climate deviates from the median. Moving window MAD time series were used to discover temporal changes in variability in hydro-climatic variables. Data is not symmetric but skewed, so instead of the mean, the median was used to measure central tendency of the data. The median is less sensitive to individual extreme values or outliers. MAD was calculated as the median of the absolute deviations from the data's median (Leys *et al.*, 2013). Standard deviation (SD) was also tested and it was found that SD was sensitive to extremes and outliers in data drawn from a non-normal distribution, giving too much weight to individual extremely high values.

Moving window MAD time series involved calculating MAD on smaller data subsets (series of data with a chosen width of a window). The window was moved forward one step at a time from the first year till the last year of the time period. Each step had a length of 1 year and after each step, the MAD for particular window was calculated. The width of the window had to be long enough to reduce noise from the data so that the constructed moving window MAD time series were readable, and at the same time short enough to catch inter-annual hydro-climate variability without the decadal variability. Multiple widths of the window were tested, and widths of 11 and 21 years were chosen to be used for the analysis. These two widths of the window were selected, because they capture different kinds of variability in data. A wider window captures longer term variability and by increasing the averaging period (the width of the window) from 11 to 21 years, change in variability was considerably reduced.

The moving window MAD time series were standardized by dividing each MAD value by the mean of the constructed moving window MAD time series. This standardizing method was used instead of the usual method of subtracting the mean and dividing by the standard deviation, because that method can be inappropriate for zero-bound data (Mimmack *et al.*, 2001), such as precipitation. Standardized time series capture relative rather than absolute changes in variability. Standardization was performed so that variables measured at different scales contribute equally to the subsequent analyses and are therefore comparable. Each variable for each time series has an equal mean value of 1. The reported coefficient of MAD therefore measures variability in relative terms, defined as the ratio of each MAD value to the mean of the MAD time series. It is a dimensionless measurement, similar to the coefficient of variation, so variability of the source data with different units is comparable.

## 2.4 Identifying areas with similar hydro-climatic variability

Principal component analysis (PCA) (Jolliffe, 2002) and agglomerative hierarchical clustering (Gong and Richman, 1995) were used to identify spatial patterns in changing variability of hydro-climatic variables in annual and seasonal scales, i.e. to discover areas where temporal hydro-climate variability changes similarly. The analysis follows the method of Mimmack et al. (2001).

PCA was used to reduce dimensionality and amount of the data, while still retaining most of the variability of the source data. PCA for standardized moving window MAD time series of each sub-basin were carried out in T-mode (Richman, 1986) by using singular value decomposition of the data matrix. In T-mode, the data matrix is formed so that it had time as columns and sub-basins as rows. This simplifies the time series and identifies spatial patterns, rather than simplifying spatial variation and identifying temporal patterns, as in S-mode. The number of retained principal components was determined using the criterion of cumulative percentage of total variation. The cutoff level was chosen such that the retained principal components account for 90% of total variation, which was deemed to be sufficient for the purpose of identifying clusters of similar MAD time series.

In agglomerative hierarchical clustering, each data point was initially treated as an individual cluster. Then at each step of clustering, the two most similar clusters were combined as a new cluster, until finally there was only a single cluster including all data points. Clustering was carried out based on Ward's minimum variance method (Ward, 1963), which minimizes the total within-cluster variance. At each step, merged pair of clusters leads to minimum increase in variance of combined clusters (Murtagh and Legendre, 2014).

The optimal number of clusters was determined using several different methods together: the R package called NbClust (Charrad *et al.*, 2014, 2015), cluster dendrograms (treelike hierarchical diagrams) (Krumbein and Graybill, 1965) and time series for each cluster. NbClust provides 30 indices, which uses different methods to determine the optimal number of clusters in the data. The package has been developed to compare these indices and to suggest the best clustering scheme. In cluster dendrograms, distance between clusters (dissimilarity) was presented on vertical axis and different data points (sub-basins) were listed on horizontal axis. Clusters were chosen such that the (visual) distance between clusters was maximized and the distance within clusters was minimized. In most of the cases results from NbClust and dendrograms were similar and the optimal number of clusters was chosen based on those. As a last step in choosing the number of clusters, time series for that certain number of clusters were produced and examined to make sure chosen clustering scheme describes as clear as possible the characteristics of changing variability in those areas. Selecting too few clusters proofed to oversimplify phenomena by grouping areas that were still substantially different, and choosing too many clusters made it difficult to draw any insight from the cluster maps as well as see differences in time series.

## 2.5 Detecting direction and statistical significance of changes in hydro-climatic variability

The direction and statistical significance of changes in hydro-climatic variability for each sub-basin was studied using the test for a monotonic trend in variances (Noguchi and Gel, 2010; Gastwirth *et al.*, 2015), which is based on the finite-intersection approach, the Brown-Forsythe transformation and Kendall's Tau coefficient. The finite-intersection approach (Mudholkar *et al.*, 1993, 1995) combines p-values of the component test statistics which correspond to a finite number of nested hypotheses. Fisher's p-value combination method (Fisher, 1934) is used in this study. The idea of nested hypotheses, breaking down the original hypothesis into a number of more manageable components, was originally suggested by Hogg (1961). In this case, the test of each hypothesis involves determining the statistical significance of the difference between variability in nested subgroups. The subgroups are defined by splitting the data into subsets of equal length, corresponding to a chosen window width. The first subgroup is compared to the second subgroup, then these subgroups are combined and compared to the next subgroup, until finally all except the last subgroup is compared to the final one. The Brown-Forsythe transformation (Brown and Forsythe, 1974), which is a robust modification of Levene's transformation, was used in this study, meaning that variability is effectively measured using MAD rather than standard deviation. Roughly speaking, the presence and significance of a trend is given by correlation between the absolute deviations of the nested groups. If the correlation is positive, the MAD increases between the groups. The nonparametric, distribution-free Kendall's Tau coefficient (Kendall, 1975) was used to allow identification of possible non-linear trends. Because of the small number of data points, the bootstrap version of test is used, as recommended by Lim & Loh (1996).

Two widths of the analysis window were used to study the statistical significance of changes in variability. Windows of 11 and 21 years were used so that they match with window widths used in construction of moving window MAD time series, however, in this case, the windows are non-overlapping. Tests were performed using a 95% significance level and one-sided tests, determined by the direction of the trend indicated by the Kendall correlation across all sub-groups, consistent with the approach used by the trend test itself.

Different non-overlapping windows can be defined within the overall 53 year time period, and the choice of window affects the result. How the time series is split into groups affects the variance of each group, and therefore the evaluation of homogeneity. To overcome this issue, repeated tests were used, with the non-overlapping windows starting in different years. The test was repeated until the ending point of the last window is set to the last year of the study period. With the 11-year window, 10 repeated tests were done to cover the whole time period and 12 repeated tests in the case of the 21-year window.

In addition to the direction of the trend, the results report both areas where all tests show statistical significance, and areas where at least one of the tests shows statistical significance. The former indicates that the assessment of statistical significance is robust. The latter indicates that a statistically significant change in variance may exist, but that further investigation is needed regarding how the time series is divided.

# 3 Results

This section shows the results of the analysis and some interpretation. First in Section 3.1, trends in hydro-climate at study area scale are presented as a background for hydro-climatic variability, which is the focus of present study. The Section 3.2 shows temporal changes in hydro-climatic variability for the study area as a whole. A more detailed view of changing variability is given in Section 3.3, where spatial patterns in changing variability are shown.

## 3.1 Hydro-climatic trends in study area scale

Time series of annual and seasonal mean temperature, precipitation sum and runoff sum are shown in Figure 1. In the case of temperature, statistically significant positive trends were found using the Mann-Kendall test both at annual and seasonal scale for all seasons. Statistically significant positive trends were also found for annual, winter and summer precipitation, as well as winter runoff.

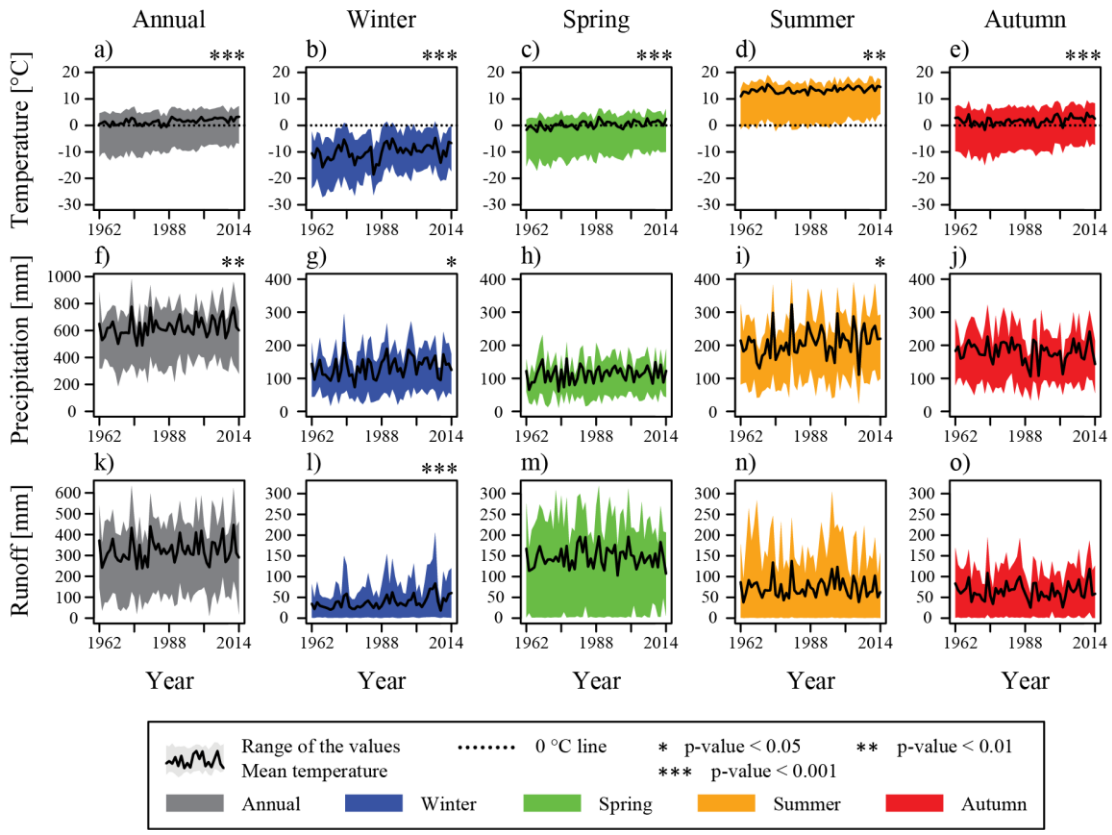


**Figure 1** Annual and seasonal mean temperatures, precipitation sums and runoff sums in the study area over period of 1962-2014. The black solid line represents the mean value of spatially averaged hydro-climatic variables and colored area around it represents the range in which values for individual sub-basins vary. In the case of seasonal precipitation and runoff, range is presented from minimum to 95th percentile, omitting outliers with extremely high values. Asterisks on right upper corner of the time series indicates that trend is statistically significant according to the Mann-Kendall test.

## 3.2 Temporal changes in hydro-climatic variability in study area scale

Study area scale averaged moving window MAD time series show the temporal changes in variability of temperature, precipitation and runoff (Figure 2).

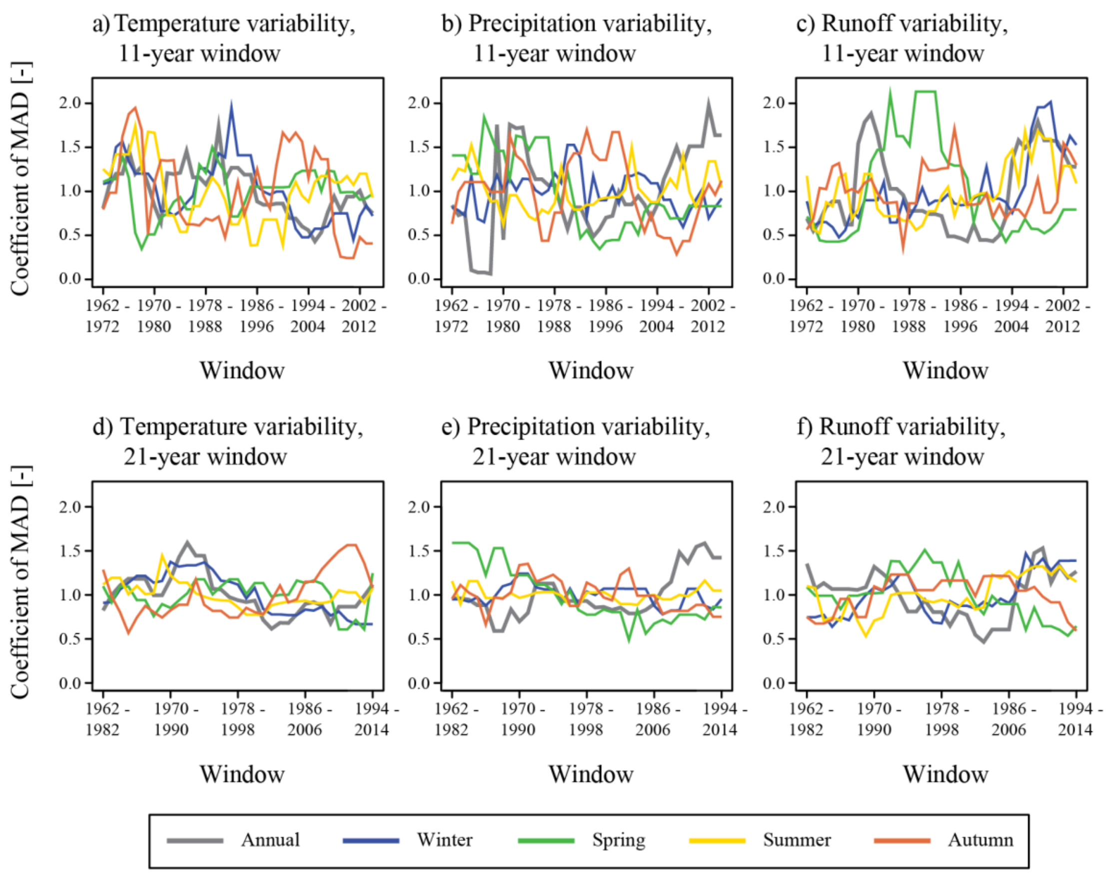


**Figure 2** Coefficient of median absolute deviation (MAD) for annual and seasonal mean temperature, precipitation sum and runoff sum in the study area over period of 1962-2014. Figure presents how variability of hydro-climatic variables have changed during the study period. Graphs a) and d) are for mean temperature with different window widths, b) and e) for precipitation sums, d) and f) for runoff sums. The x-axis shows start and end years of analysis windows. The y-axis shows relative MAD values (coefficient of MAD).

The moving window MAD time series of mean temperature (Figure 2a; Figure 2d) show decrease in annual and winter variability with both widths of window. In both cases, some analysis windows identify the trend as statistically significant. In the case of spring and summer, there is neither clear increase nor decrease in changing variability. For autumn variability, an increase is identified with a 21-year window, but a decrease with the shorter 11-year window. These changes are not statistically significant. Given that the longer window reacts more slowly to changes in hydro-climate than the shorter window, a possible interpretation is that the trend in autumn variability is changing direction, from the longer term increase indicated by the 21-year window, to the emerging decrease, indicated by the 11 year window.

In terms of precipitation sums (Figure 2b; Figure 2e), both window widths show an increase in variability of annual precipitation sum, but changes are not statistically significant. Variability in winter and spring precipitation is decreasing and in case of spring most of the analysis windows show statistically significant trend. In summer, variability is increasing but trend is not statistically significant, and in autumn, there are no clear increases or decreases in precipitation sum variability at study area scale.

Moving MAD time series of runoff sums (Figure 2c; Figure 2f) show an increase in winter and summer variability but the changes are not statistically significant. For annual, spring and autumn, no long-term changes were found regarding variability of runoff sums at study area scale.

## *3.3 Spatial patterns in changing variability and statistical significance of changes*

Principal component analysis and agglomerative hierarchical clustering revealed spatial patterns in changing variability. Results are presented as maps showing areas (clusters of sub-basins) where variability of each hydro-climatic variable is changing similarly. Furthermore, moving window MAD time series of these areas with similar changes are presented to describe characteristics of the hydro-climatic variability. These maps and time series for mean temperature (Figure 3), precipitation sum (Figure 4) and runoff sum (Figure 5) are presented in this section. Moreover, the test for a monotonic trend in variances identified statistical significance of changes in hydro-climate variability. Areas with statistically significant changes are presented in Figure 6, Figure 7 and Figure 8.

These results suggest a decreasing trend in variability for the whole study area for annual and winter mean temperature (Figure 3a-d). These changes in variability are statistically significant in most parts of the study area (Figure 6a-b; Figure 6f-g). For summer mean temperature variability, a statistically significant decrease was found in northern Finland (Figure 3g-h; Figure 6d; Figure 6i).

With regards to annual precipitation variability, statistically significant decreases were found in southern parts of Finland (Figure 4a-b; Figure 7a; Figure 7f) even though at study area scale, variability was found to increase (Figure 2b; Figure 2e). Statistically significant decreases were also found in spring precipitation variability in the central part of the study area (Figure 4e-f; Figure 7c; Figure 7h). In the case of autumn precipitation variability, a statistically significant increase in northern Finland and a decrease in southeastern Finland was found (Figure 4i-j; Figure 7e; Figure 7j).

For runoff variability in most parts of the study area, a statistically significant increase was found in winter runoff (Figure 5c-d; Figure 8b; Figure 8g) and a statistically significant decrease in spring runoff (Figure 5e-f; Figure 8c; Figure 8h). Moreover, in summer variability, statistically significant increases were found in the middle part of the study area (Figure 5g-h; Figure 8d; Figure 8i).

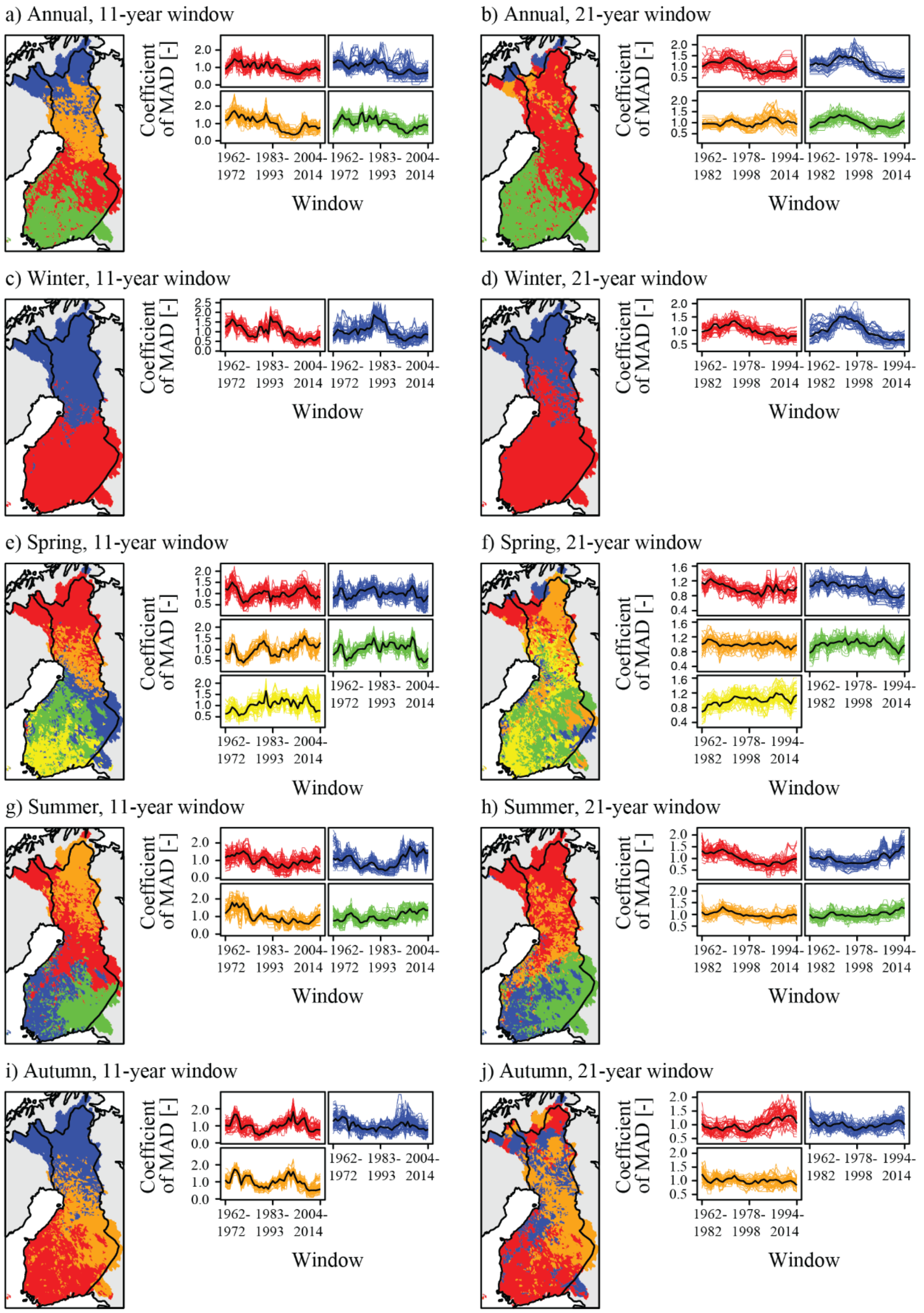


**Figure 3** Changes in variability of annual and seasonal mean temperature in the study area over period of 1962-2014. Maps and time series a) and b) are showing annual variability with window widths of 11 and 21 years, c) and d) winter variability, e) and f) spring variability, g) and h) summer variability, i) and j) autumn variability. Maps show areas with similarly changing variability using different colors. Accompanying time series show the time series of variability for the corresponding areas. In time series, the x-axis shows the start and end years of analysis windows, and the y-axis shows relative median absolute deviation (MAD) values.

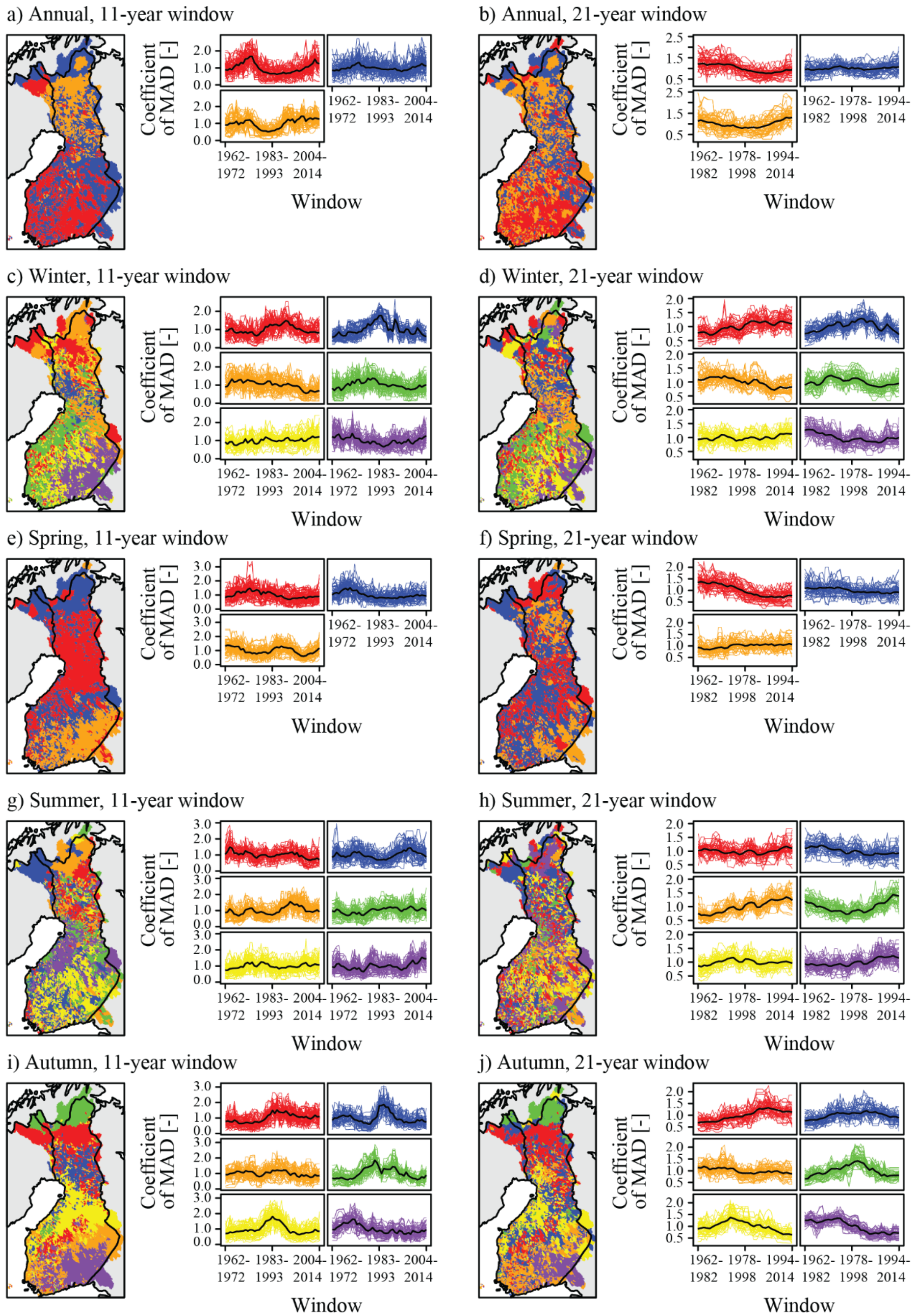


**Figure 4** Changes in variability of annual and seasonal precipitation sums in the study area over period of 1962-2014. Maps and time series a) and b) are showing annual variability with window widths of 11 and 21 years, c) and d) winter variability, e) and f) spring variability, g) and h) summer variability, i) and j) autumn variability. Maps show areas with similarly changing variability using different colors. Accompanying time series show the time series of variability for the corresponding area. In time series, the x-axis shows start and end years of analysis windows, and the y-axis shows relative median absolute deviation (MAD) values.

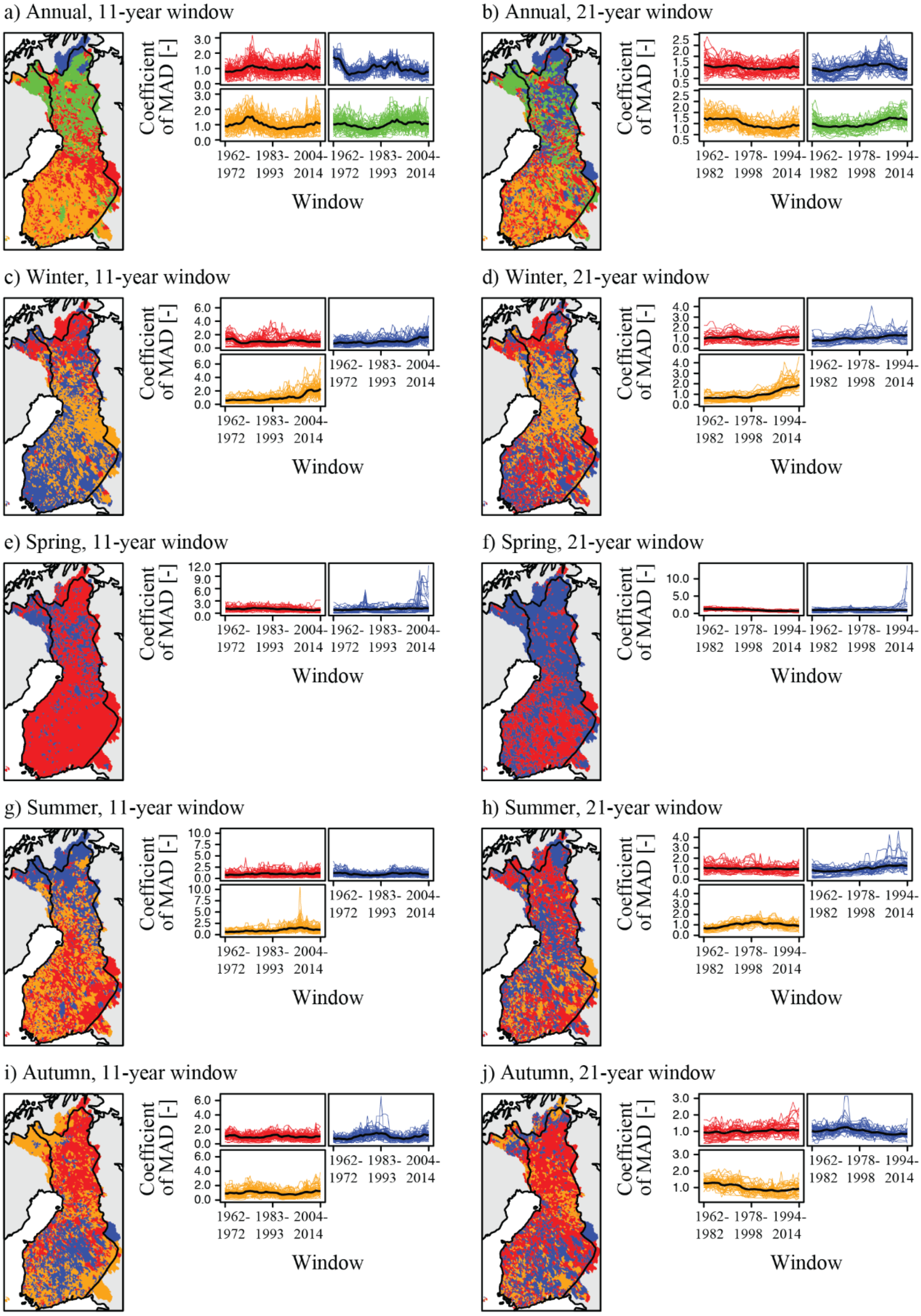


**Figure 5** Changes in variability of annual and seasonal runoff sums in the study area over period of 1962-2014. Maps and time series a) and b) are showing annual variability with window widths of 11 and 21 years, c) and d) winter variability, e) and f) spring variability, g) and h) summer variability, i) and j) autumn variability. Maps show areas with similarly changing variability using different colors. Accompanying time series show the time series of variability for the corresponding area. In time series, the x-axis shows start and end years of analysis windows, and the y-axis shows relative median absolute deviation (MAD) values.

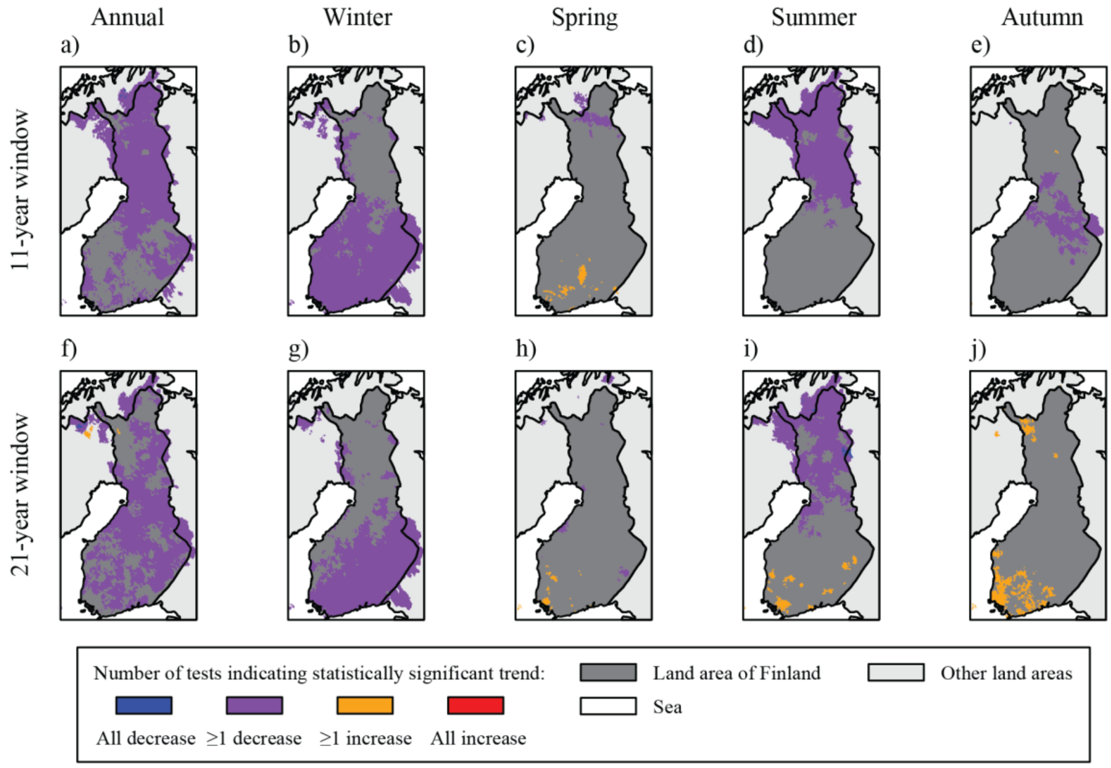


**Figure 6** Areas where changes in variability of annual and seasonal mean temperature are statistically significant ($p<0.05$) over period of 1962-2014. Maps a) – e) show results from 10 repeated tests with different start years for a monotonic trend in variances with 11 years width non-overlapping window and maps f) – j) results from 12 repeated tests with 21 years width window. Red and blue colors indicate areas where trend is statistically significantly increasing or decreasing. Orange and purple colors indicates areas where at least one of repeated tests shows statistically significant increasing or decreasing trend in variability.

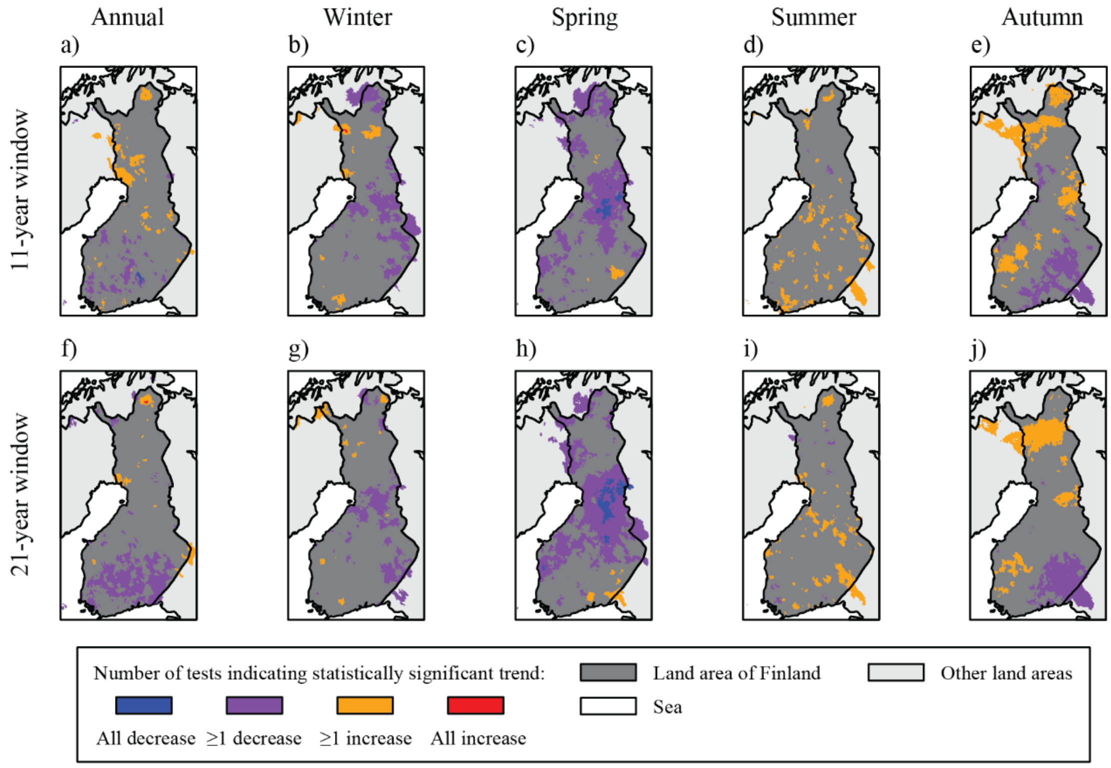


**Figure 7** Areas where changes in variability of annual and seasonal precipitation sums are statistically significant ($p<0.05$) over period of 1962-2014. Maps a) – e) show results from 10 repeated tests with different start years for a monotonic trend in variances with 11 years width non-overlapping window and maps f) – j) results from 12 repeated tests with 21 years width window. Red and blue colors indicate areas where trend is statistically significantly increasing or decreasing. Orange and purple colors indicates areas where at least one of repeated tests shows statistically significant increasing or decreasing trend in variability.

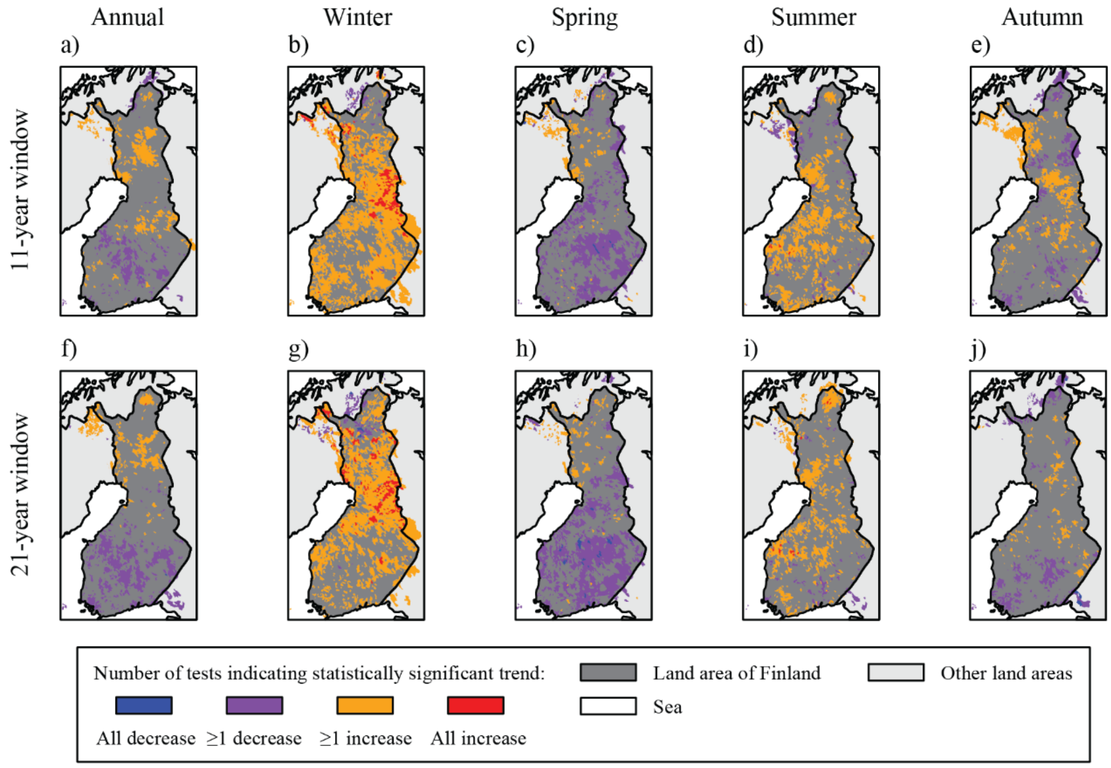


**Figure 8** Areas where changes in variability of annual and seasonal runoff sums are statistically significant ($p<0.05$) over period of 1962-2014. Maps a) – e) show results from 10 repeated tests with different start years for a monotonic trend in variances with 11 years width non-overlapping window and maps f) – j) results from 12 repeated tests with 21 years width window. Red and blue colors indicate areas where trend is statistically significantly increasing or decreasing. Orange and purple colors indicates areas where at least one of repeated tests shows statistically significant increasing or decreasing trend in variability.

# 4 Discussion

Analyses in this study were carried out using a sub-basin scale annual and seasonal mean temperature, precipitation sum and runoff sum dataset in Finland for the period of 1962-2014. Results from the analysis give a very mixed picture, with trends and patterns of variability differentiated spatially and by season. However, some clear areas were found where hydro-climatic variability follows similar patterns of change on annual and/or seasonal scale. This section discusses results of this study in relation to previous studies. In addition, limitations of the present study and how they were treated, as well as suggestions for future research directions are discussed.

## *4.1 Comparison to previous studies*

In this study, sub-basin scale data were used instead of grid scale data (Irannezhad *et al.*, 2014a, 2014b) or data from just few observation stations (Korhonen, 2007; Wilson *et al.*, 2010) as in previous studies. Results of this study are, however, well in line with previous studies, in terms of trends in mean hydro-climate during the time period of 1962-2014 (Section 3.1). Statistically significant positive trends were found for annual, winter and summer precipitation sums, similarly in the study by Irannezhad et al. (2014b). Also in case of annual, spring and summer mean temperature, statistically significant positive trends were found in present study as well as previous studies by Jylhä et al. (2004), Irannezhad et al. (2014a) and Mikkonen et al. (2015). Furthermore, the current study also found statistically significant positive trends in winter and autumn mean temperature. Results about trends in runoff sums showed statistically significant increase in winter, which is comparable to studies about discharge by Hyvärinen (2003), Korhonen (2007) and Wilson et al. (Wilson *et al.*, 2010).

Previous studies focus mainly on trends in mean state of climate and not on changes in variability. Consistent with expectation (IPCC, 2001), results of present and previous studies show that changes in mean state of climate does not necessarily mean parallel changes in climate variability. For example, whereas mean annual temperature is increasing according to this (Figure 1) and previous studies (Jylhä *et al.*, 2004; Irannezhad *et al.*, 2014a; Mikkonen *et al.*, 2015), the current study shows inter-annual variability in mean temperature to be decreasing (Figure 2a; Figure 2d). On the other hand, results from present study on changes in annual precipitation sum variability (Figure 2b; Figure 2e) and previously studied mean precipitation sum trends (Irannezhad *et al.*, 2014b), both show increases at study area scale. Furthermore, previous studies have found significant increases in winter and summer mean precipitation sum, however the variability does not show clear changes in present study. These examples illustrate the importance of assessing variability as well as mean hydro-climate, as was the aim of this study.

There are similarities between the current study and that by Giorgi & Bi (2005) regarding continental scale temperature and precipitation variability. This study found decreasing trends for winter temperature and precipitation in Finland, which agrees with their projections for northern Europe. For the summer, they project an increasing trend for both precipitation and temperature, while this study found increases in precipitation in some areas and decrease in temperature in northern Finland. Giorgi & Bi (2005) used an ensemble of general circulation models and reported an average value across models as a result. The models include notable inter-model variation, which lead to an uncertainty of estimating changes in variability.

## 4.2 Limitations of the present study

Key assumptions of the study include the selection of width of moving windows, definition of clusters, and selection of the source data to be analyzed. Moving windows and clustering are commonly used methods in time series analysis and the way they are used in present study is considered to provide robust scientific results.

Firstly, in analysis of statistical significance of changes hydro-climate variability with the test for a monotonic trend in variances, the chosen width of the window and starting year of the analysis had notable effect on results. To overcome this issue and to cover the whole time period, repeated tests were conducted with different starting years. Only a few areas were found where all the repeated test showed statistical significance (e.g. Figure 7h and Figure 8g), but more areas where at least one of repeated tests identified statistical significance. These latter areas were interpreted to indicate possible statistical significant changes in variability. This was seen to be informative and robust way to present areas where interesting changes in hydro-climatic variability may be occurring. Secondly, choosing the width of the window, or in other words the length of period, for moving window MAD time series proved to be important part in analysis of temporal changes in hydro-climatic variability. The decision to use two widths of analysis windows, 11 and 21 years, was considered suitable to detect inter-annual variability, and to show variability with different timeframes but with similar patterns.

Thirdly, the ease of identification of spatial patterns is influenced by the number of clusters used. The strength of clustering is in condensing large volumes of information. There is therefore a trade-off involved. Selecting too few clusters risks oversimplifying phenomena, and grouping areas that are still substantially different. On the other hand, selecting too many clusters makes it difficult to draw any insight from the maps and diminishes the noticeable difference between clusters. The choice of number of clusters was informed by different methods (the R package called NbClust, cluster dendrograms and cluster time series) and several options were tested. However, some subjectivity necessarily remains in the clusters identified.

Possible uncertainties and limitations that the source data may contain were not considered in this study. Factors that can cause these uncertainties can be, for example, changes in number of gauge stations in the network, missing observation values, changes in precipitation measurement methods and correction methods for gauge precipitation observations. The runoff data is simulated with the WSFS hydrological model and not observed, and may therefore contains uncertainties linked with model structure and parameters. The results are therefore interpreted to represent climate variability as captured by the reference source data provided by SYKE. By providing an overview for the whole of Finland, this study identifies hotspots that may be of interest for further, more detailed, study.

## 4.3 Future research directions

The present study analyzed changes in variability and thus provides a basis for more in-depth analysis of extreme events and changes in their frequency and intensity. At a global scale, frequency and intensity of the extremes have been projected to change (IPCC, 2015), but this change has not yet been documented in Finland. An increase in variability implies an increase in the probability as well as the absolute values of the extremes (IPCC, 2001), however, it should be noticed that the effect of change in variability on extremes depends on change in mean state. Future studies could focus on floods, droughts, heavy rains and heat waves specifically.

Moreover, it would be interesting to study more specific hydro-climatic variables and how their variability has changed, for example, the start and end date of thermal seasons, snow water equivalent, as well as snow accumulation and melt.

Future studies may also focus on causes behind the identified changes in hydro-climatic variability. In climate change studies, correlation between trends of climatic variables and different teleconnections, e.g. North Atlantic Oscillation (NAO), is previously widely studied and the studies show that teleconnections are highly linked to global and regional climate change (Wanner *et al.*, 2001; Hurrell *et al.*, 2003; Hurrell and Deser, 2010). Teleconnections themselves are varying and changing phenomena, and their effects on hydro-climate can therefore also change in time. In the case of Finland, interesting teleconnections to study, amongst others, would be the NAO and Arctic Oscillation (AO), which have already been studied in Finland to some extent, but their linkage to the changes discovered in this study are not known. Furthermore, recent studies have already linked e.g. East Atlantic/West Russia (EA/WR), Scandinavia (SCA) and Polar/Eurasia (POL), at least to changes in mean temperature (Irannezhad *et al.*, 2014a) and precipitation (Irannezhad *et al.*, 2014b), though connections to variability have not been addressed.

Finally, another possible future research direction could be to predict how climate variability will change in the coming years and decades in Finland, using different climate change scenarios, as well as a historical analysis of information dating further back in time, if reliable data is available. Based on the present study, changes in hydro-climatic variability are clearly significant enough, as well as spatially and temporally complex enough, to warrant additional research. Moreover, hydro-climatic variability and extreme events related to it, affects various sectors of society, as discussed in the Introduction section. Further and more detailed research is needed to improve understanding of spatial and temporal changes in hydro-climatic variability in Finland, as well as identifying the sectors of society affected. This would improve the possibility to adapt to and predict the changing hydro-climatic conditions.

# 5 Conclusions

This study assessed the spatial and temporal inter-annual changes in hydro-climatic variability in Finland. Specifically, changes in variability of temperature, precipitation and runoff were analyzed using a sub-basin scale dataset at both annual and seasonal scales over the period of 1962-2014 and statistical analyses, median absolute deviation, principal component analysis, agglomerative hierarchical clustering, and the test for a monotonic trend in variances.

Results give a mixed picture, with trends and patterns of hydro-climatic variability differentiated by season and location. However, some clear areas were found, where changing hydro-climatic variability follow similar patterns. In terms of temperature, the present study found statistically significant decreases in annual and winter mean temperature variability for most parts of Finland as well as for summer in northern Finland, respectively. For precipitation sum variability, present study found an increase in annual variability at study area scale.

In addition to that, this study suggests statistically significant decrease in annual precipitation variability in southern parts of Finland, which indicates that there are substantial spatial differences within the study area. Furthermore, statistically significant decreases are suggested for spring and autumn precipitation variability in the middle parts of Finland and increase for autumn in northern Finland. With regard to runoff sum variability, winter and summer variability showed increases in study area scale and for winter this increase was statistically significant in middle parts off Finland.

Previous and present studies together show that changes in mean state of hydro-climate does not necessarily mean parallel changes in hydro-climatic variability. This demonstrates the importance of this study's focus on climate-induced changes in hydro-climatic variability rather than only trends in hydro-climatic mean conditions. The presented findings thus provide new information on hydro-climatic variability in Finland, particularly as it relates to observed rather than predicted climate change.

Different sectors of society are affected by extreme hydro-climatic events, positively or negatively. Changing hydro-climate variability, as well as mean state of hydro-climate, results in changes in frequency and intensity of these extreme events. For this reason it would be important to identify which sectors are indeed affected by changing hydro-climatic conditions and evaluate how they are affected. This line of research has the potential to better prepare people and infrastructure so as to improve the possibility to adapt and predict the changes in hydro-climatic conditions, including weather extremes.

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